

Application
for
United States Letters Patent

To all whom it may concern:

Be it known that,

Hwan J. JEONG and Xing CHEN

have invented certain new and useful improvements in

OPTICAL INTERLEAVING WITH ENHANCED
SPECTRAL RESPONSE AND REDUCED POLARIZATION SENSITIVITY

of which the following is a full, clear and exact description:

030544-0100

**OPTICAL INTERLEAVING WITH ENHANCED
SPECTRAL RESPONSE AND REDUCED
POLARIZATION SENSITIVITY**

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Xing Chen

FIELD

This patent specification relates to fiber optic communication systems. More particularly, it relates to optical interleaving for combining and/or separating optical signals.

BACKGROUND

As the world's need for communication capacity continues to increase, the use of optical signals to transfer large amounts of information has become increasingly favored over other schemes such as those using twisted copper wires, coaxial cables, or microwave links. Optical communication systems use optical signals to carry information at high rates over an optical path such as an optical fiber. Optical fiber communication systems are generally immune to electromagnetic interference effects, unlike the other schemes listed above. Furthermore, the silica glass fibers used in fiber optic communication systems are lightweight, comparatively low cost, and are able to carry tens, hundreds, and even thousands of gigabits per second across large distances.

Indeed, one 1998 experiment was reported in which a single optical fiber successfully transported 2,640 gigabits per second of information across a 120 km distance; see Dutton, *Understanding Optical Communications* (Prentice Hall 1998), which is incorporated by reference herein, at p. 6. According to Dutton, *supra*, this single optical fiber was transporting enough data to simultaneously carry the maximum number of telephone calls in existence on Earth at any particular moment in time (about 30 million calls in 1998). Most practical commercial systems operate at lower data rates, of course, although progress continues in increasing the data rate of practical optical communication systems.

Today's long-distance fiber optic communication systems generally use single-mode optical fibers to transport light at wavelengths between 1530 nm and 1570 nm in the

infrared spectrum. As known in the art, the 1530-1570 nm range is the operational range of Erbium-doped fiber amplifiers (EDFAs), which are currently used in practical long-distance fiber optic communications links. Also, the 1530-1570 nm range is where current single-mode fibers have relatively low attenuation (about 0.26 dB/km). Accordingly, it is desirable to carry as much information as possible in this 1530-1570 nm wavelength band. However, known current electro-optical modulators are only capable of modulating light at a rate of about 10 GHz, corresponding to a wavelength spread of only about 0.16 nm. To efficiently use the entire 1530-1570 nm spectrum, wavelength-division multiplexing (WDM) is used, wherein a plurality of light beams are separately modulated and are then optically combined onto a single optical fiber. To maximize the use of available spectrum, as many channels as possible are multiplexed together into the 1530-1570 nm band in what are often referred to as dense wavelength-division multiplexing (DWDM) systems.

FIG. 1 shows a portion of a spectrum 102 of a typical DWDM signal, in which forty channels are spaced 50 GHz apart (0.4 nm apart) and multiplexed onto a single optical fiber. The width of each channel depends on the specific modulation scheme and modulation rate for that channel, but the channels are shown generally in FIG. 1 as having a width of about 20 GHz (0.16 nm). For increased efficiency and network throughput, it is desirable to increase the number of channels multiplexed onto the single fiber, while also retaining the ability to effectively filter out ("drop") or add in ("add") any given channel on the fiber at a given point. The ability to add and drop individual channels from a data stream is, of course, central to the construction of DWDM-based optical communication networks. In FIG. 1, for example, it is necessary to be able to filter out channel 104 without crosstalk effects from neighboring channels 106 and 108.

As international standards continue to reduce DWDM channel spacings, conventional dichroic filters used in add/drop devices have not been able to keep up in terms of the narrowness of their passband, with the known best dichroic filters only achieving effective channel separation for channel spacings of about 100 GHz or greater. To address this problem, optical interleavers have been introduced that are capable of operating on a DWDM signal carrying channels at wavelength ($\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$) to produce two output signals carrying channels at ($\lambda_1, \lambda_3, \lambda_5, \dots$), and ($\lambda_2, \lambda_4, \lambda_6, \dots$),

respectively. Because the channel spacings are now doubled, it is easier for conventional dichroic filters to operate on the signal to drop and/or add the channels of interest.

An idealized optical interleaver is shown as element 110 in FIG. 1, comprising an input port 112 for receiving the initial DWDM signal 102 and two output ports 114 and 116 for generating the output signals 118 and 120, respectively. The idealized filter function from input port 112 to output port 114 is represented by I_{even} while the idealized filter function from input port 112 to output port 116 is represented by I_{odd} . As indicated in FIG. 1, the ideal spectral response of an optical interleaver is a perfectly square or box-like response. As described *infra*, practical optical interleavers will generally have passband characteristics with narrower tops and wider bottoms than the ideal.

Unless otherwise indicated, it is to be appreciated that the interleavers described herein are reciprocal devices, with the term “interleaver” representing a device that will perform “de-interleaving” when light signals are passed through in the reverse direction in accordance with optical reciprocity principles. Thus, for example, the interleaver 110 of FIG. 1 actually works as a “de-interleaver” when provided with a signal at port 112, providing the de-interleaved outputs at ports 114 and 116, and will operate as an “interleaver” when provided, for example, with the appropriate component signals at ports 112 and 116 providing the interleaved output at port 114.

FIG. 2 shows a generic spectral response characteristic 202 of one output port of a practical optical interleaver, which differs from the idealized optical interleaver 110 in that the passbands are not perfectly square. Different metrics are used to evaluate the squareness of the interleaver passbands, one such set being shown in FIG. 2. The metric FSR_{out} is the free spectral range of the output, *i.e.*, the distance between transmission peaks, which is usually twice the input channel spacing Δf . Whereas the spectral response characteristic 202 may represent the “even” output channels from a first output port, there is complementary spectral characteristic (not shown) for the “odd” channels which is similar to the curve 202 shifted by Δf . The metrics $W_{0.1\text{dB}}$, $W_{0.5\text{dB}}$, $W_{3\text{dB}}$, $W_{20\text{dB}}$, and $W_{30\text{dB}}$ represent the width of the spectral curve around one of the passbands of the optical interleaver at spectral power attenuations of 0.1 dB, 0.5 dB, 3dB, 20 dB, and 30dB, respectively, as shown in FIG. 2, and may be represented in distance (nm) or corresponding frequency (GHz) units.

For an ideal interleaver having a perfect box-like response, each of the values $W_{0.1dB}$, $W_{0.5dB}$, W_{3dB} , W_{20dB} , and W_{30dB} would be equal to Δf . In general, the closer that all of these values are to Δf , the better the performance of the optical interleaver as there is reduced crosstalk between channels and less distortion in the passed signals. It is

- 5 particularly desirable to make an optical interleaver having both $W_{0.1dB}$ and $W_{0.5dB}$ as wide as possible to create a flat passband for reduced distortion. It is also desirable to make an optical interleaver having both W_{20dB} and W_{30dB} as narrow as possible to reduce crosstalk between a passed channel (e.g., λ_2) and its immediately neighboring channels (e.g., λ_1 and λ_3). For comparative purposes, the values of the width metrics $W_{0.1dB}$, $W_{0.5dB}$, etc., may be
- 10 normalized by the input channel spacing Δf and/or the free spectral range FSR_{out} , in which case their optimal normalized values would be 1.0 and 0.5, respectively. Unless otherwise indicated, in the present disclosure the width metrics $W_{0.1dB}$, $W_{0.5dB}$, etc. will be normalized by the input channel spacing Δf .

- FIG. 3 shows an optical interleaver 300 according to the prior art, in the form of a
- 15 classical Michelson interferometer. Optical interleaver 300 comprises a beamsplitter 302 for dividing an incoming beam, received at an input port 301 and having WDM channels at $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots)$, into a first beam 304 and a second beam 306, respectively, these beams being separated by 90 degrees as shown in FIG. 3. Optical interleaver 300 further comprises a first mirror 308 for receiving and reflecting the first beam 304 back to the
- 20 beamsplitter 302, and a second mirror 310 for receiving and reflecting the second beam 306 back to the beamsplitter 302, to the same point on the beamsplitter 302 as the first reflected beam. The beamsplitter 302, which also operates as an optical combining device, causes the first and second beams 304 and 306 to interferometrically combine to produce a first output 312 and a second output 314. Distances L_1 and L_2 separate the beamsplitter
- 25 302 from the first mirror 308 and the second mirror 310, respectively. As known in the art, taking into account the total optical path $\sum L_i \eta_i$ traversed by each of the first beam 304 and second beam 306, including glass portions or other material in which η_i is greater than 1, the dimensions L_1 and L_2 may be selected such that, for the first output 312, constructive interference occurs for the odd wavelengths $(\lambda_1, \lambda_3, \lambda_5, \dots)$ and destructive interference
- 30 occurs for the even wavelengths $(\lambda_2, \lambda_4, \lambda_6, \dots)$. Likewise, using these dimensions, for the second output 314 there will be constructive interference for the even wavelengths $(\lambda_2, \lambda_4,$

λ_6, \dots) and destructive interference for the odd wavelengths ($\lambda_1, \lambda_3, \lambda_5, \dots$). The second output 314 containing the even wavelengths may then be separated from the incoming beam using a circulator (not shown).

The optical interleaver 300, however, contains several shortcomings which would

5 limit its use as a practical interleaving device. First, it can be readily shown that the transmission response of either output, for example the even output 314, is merely a sinusoidal function having maxima at ($\lambda_2, \lambda_4, \lambda_6, \dots$) and minima at ($\lambda_1, \lambda_3, \lambda_5, \dots$). In particular, the transmission characteristic metrics defined *supra* would be approximately $W_{0.1dB} = 0.19\Delta f$, $W_{0.5dB} = 0.43\Delta f$, $W_{3dB} = 1.00\Delta f$, $W_{20dB} = 1.87\Delta f$, and $W_{30dB} = 1.96\Delta f$.

10 These values would lead to large amounts of crosstalk and signal distortion.

Moreover, the optical interleaver 300 is polarization-sensitive, the output being degraded if the incident light is partially or totally polarized. This is due to the fact that the beamsplitter 302 as configured in FIG. 3 will not perform a precise 50/50 split of incident light that is partially or totally polarized. In turn, it is this precise 50/50 split that is

15 depended upon for proper constructive and destructive interference of the reflected beams. It has been found that even when unpolarized light is introduced into a fiber in a real-world optical fiber communication system, unwanted polarizations can arise due to many different factors, such as excessive twists or loops in the optical fiber. It is therefore required that optical interleavers be insensitive to polarizations in the incident light beam.

20 Finally, the optical interleaver 300 is not thermally robust, with the output degrading upon substantial temperature fluctuations sufficient to change the index of refraction of the glass (or other optical material) portions of the optical paths of beams 304 and 306. In particular, when the temperature rises and the refractive index η of the glass portions increase, the beam 306 will be retarded by a greater amount than beam 304

25 because it travels through more glass than beam 304. This, in turn, disturbs the phase relationships required for proper constructive and destructive interference, degrading the operating characteristics of the optical interleaver.

Some proposals have been made for providing split-beam interferometer-based optical interleavers that provide better performance than the classical Michelson

30 interferometer, including that discussed in WO 00/48055 ("the '055 reference"), which is incorporated by reference herein. The '055 reference discusses an optical interleaver

comprising a “separator” having a surface with a 50% reflective coating oriented at what is apparently 45 degrees with respect to the incoming beam (‘055 reference, FIG. 4) that splits an incoming beam into two component beams at an apparent 90 degree angle with respect to each other. The two beams are then directed in parallel to a “nonlinear split beam interferometer,” with the reflected beams being recombined at the separator to produce the interleaved outputs. The “nonlinear split beam interferometer” (‘055 reference, FIG. 5) comprises a cavity having a front surface of 18.5% reflectivity, a rear surface of 100% reflectivity, and a “wavelength tuning element” interposed therebetween. The cavity also comprises a “180 degree phase bias element” interposed between the reflective surfaces, along with a “90 degree phase bias element” outside the cavity that is encountered by only one of the beams.

The interleaver of the ‘055 reference, however, has several disadvantages. First, although the ‘055 reference describes the 50% reflective coating on the separator to be “polarization insensitive,” it is not apparent what such material is and/or whether it can be physically realized. If not, the interleaver of the ‘055 reference would be highly polarization sensitive. It would be desirable to provide an optical interleaver having reduced polarization sensitivity that does not depend on the existence of a “polarization insensitive” reflective coating.

Second, the interleaver of the ‘055 reference will be sensitive to thermal variations. As shown in FIG. 4 therein, each split beam of the ‘055 reference encounters an identical physical distance between the separator and the cavity, with the optical path difference being created by virtue of placing glass or other solid material (the “phase bias elements”) in the path of one of the beams. However, it is well known that most materials including glass will have a refractive index η that changes with temperature, while the refractive index of air or vacuum is comparatively insensitive to thermal variations. Accordingly, the amount of optical path difference between the split beams will vary with temperature, making the interleaver of the ‘055 reference thermally sensitive and/or thermally unstable.

Third, the interleaver of the ‘055 reference comprises a cavity designed such that the split beams encounter surfaces of identical reflectivities (*i.e.*, both beams encounter front surfaces of 18% reflectivity and rear surfaces of 100% reflectivity). While some performance improvement over the classical Michelson interferometer may be realized

(e.g., a W_{20dB} of about 1.50 of the input channel spacing versus 1.87 for the classical Michelson interferometer, see '055 reference, FIG. 3, plot 340), it would be desirable to provide an optical interleaver having a spectral characteristic that is closer to the ideal box-like response.

5 Another optical device that alters a classical Michelson interferometer is discussed in EP0933657(A2) by Dingel et al ("the '657 reference"), which is incorporated by reference herein. The '657 reference discusses a "Michelson-Gires-Tournois Interferometer (MGTI)" in which one of the reflecting mirrors of a classical Michelson interferometer of FIG. 3 is replaced by a Gires-Tournois resonator having a partially

10 reflective front mirror and a fully reflecting back mirror. However, for reasons similar to those described *supra* with respect to the classical Michelson interferometer, the device of the '657 reference is sensitive to polarization of the input light. Also, the '657 reference discusses a device in which the free spectral range of the output is much greater (e.g., 30.8 nm) than that required for use as a WDM interleaver, and would fit only one passed
15 channel in the 1530-1570 nm operational range of Erbium-doped fiber amplifiers (EDFAs). Moreover, it would be desirable to provide an optical interleaver having a spectral characteristic that is still closer to an ideal box-like response.

Accordingly, it would be desirable to provide an optical interleaver for use in optical communications systems that provides an output characteristic that is close to an
20 ideal box-like response.

It would be further desirable to provide an optical interleaver that has reduced sensitivity to polarization of the incident light.

It would be still further desirable to provide an optical interleaver having increased thermal stability.

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SUMMARY

In accordance with a preferred embodiment, an optical interleaver is provided for receiving an incident beam carrying a wavelength-division-multiplexed (WDM) signal comprising a plurality of channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$ and
30 generating therefrom at least one de-interleaved output signal comprising the odd channels $\lambda_1, \lambda_3, \lambda_5, \dots$ or the even channels $\lambda_2, \lambda_4, \lambda_6, \dots$. The optical interleaver comprises a

splitting element for splitting an incident beam into a first optical signal directed along a first path and a second optical signal directed along a second path, a first resonant element positioned along the first path, a second resonant element positioned along the second path, and a combining element positioned to receive and to interferometrically combine the

- 5 outputs of the first and second resonant elements to produce the output signal. In accordance with reciprocity principles, the optical interleaver is readily adapted to operate as an interleaver, de-interleaver, or add/drop multiplexer. It has been found that the use of two resonant elements, each operating on a separate split-beam portion of the incident beam in accordance with a preferred embodiment, provides for an improved box-like
- 10 spectral response when their respective outputs are interferometrically recombined.

The optical interleaver may be implemented using a free-space configuration using a beamsplitter and a plurality of resonant cavities such as asymmetric Fabry-Perot resonators or Michelson-Gires-Tournois resonators. Preferably, the reflectivities of the inner mirrors of the two resonant cavities are different, and may be selected so as to

- 15 optimize the squareness of the spectral response. In an alternative preferred embodiment, the optical interleaver may be implemented in a Mach-Zender-style configuration using couplers and fiber ring resonators. In this preferred embodiment, the coupling ratios of the fiber ring resonators are likewise different, and may likewise be selected to optimize the squareness of the box-like spectral response.

- 20 According to a preferred embodiment in which the optical interleaver is in a free-space configuration, the splitting element that receives the incident beam comprises a partially reflective surface positioned such that a normal to the reflective surface is at a less-than-30 degree angle with respect to the incoming beam. As this angle is reduced even further below 30 degrees, the optical interleaver becomes increasingly robust against
- 25 polarizations in the incident light beam, because the splitting ratio of the reflective surface becomes increasingly stable as this angle is reduced. Angles of 10 degrees or less are even more preferable in providing an optical interleaver that is stable against polarizations in the incoming beam. Reducing the above splitting angle in accordance with the preferred embodiments will stabilize single-cavity optical interleavers as well as dual-cavity optical
- 30 interleavers.

In accordance with another preferred embodiment, thermal stability of the optical interleaver is enhanced. In particular, the first and second paths traversed by the respective split-beam portions will each include a preliminary thickness of optical material associated with the splitting element, the first and second resonant cavities, or other optical elements.

- 5 The amount of glass or other optical material in these paths may often differ depending on the nature of the components used, the free-space distances between the optical elements, and the channel spacing of the WDM signals on the incident beam. In accordance with a preferred embodiment, a compensating optical element is placed along the first or second path as required to equalize the collective thickness of optical material in the first and
- 10 second paths, with any free-space distances being adjusted as required to maintain the proper optical path length difference between the first and second path. Accordingly, if the operating temperature increases and substantially changes the refractive index of the optical material, thereby changing the optical path length through the optical material, any changes in the optical paths lengths of the first and second paths will offset each other,
- 15 thereby providing for a thermally stable optical interleaver.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows an idealized optical interleaver and spectral characteristics of input and output signals corresponding thereto;

- 20 FIG. 2 shows a spectral characteristic of an output of a practical optical interleaver;
- FIG. 3 shows a Michelson interferometer-based optical interleaver according to the prior art;

FIG. 4 illustrates a dual resonant element optical interleaver in accordance with a preferred embodiment in a de-interleaving configuration;

- 25 FIGS. 5A and 5B illustrate spectral characteristics of the outputs of the optical interleaver of FIG. 4;

FIG. 6 illustrates a single resonant element optical interleaver in accordance with a preferred embodiment in a de-interleaving configuration;

- FIGS. 7A and 7B illustrate spectral characteristics of the outputs of the optical
- 30 interleavers of FIGS. 4 and 6;

FIG. 8 illustrates an optical interleaver according to a preferred embodiment in an interleaving configuration;

FIG. 9 illustrates an add/drop multiplexer in accordance with a preferred embodiment;

5 FIG. 10 illustrates a Mach-Zender implementation of a dual resonant element optical interleaver in accordance with a preferred embodiment; and

FIG. 11 illustrates a Mach-Zender implementation of a dual resonant element optical interleaver in accordance with a preferred embodiment in an add/drop multiplexer configuration.

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DETAILED DESCRIPTION

FIG. 4 illustrates an optical interleaver 400 in accordance with a preferred embodiment. Optical interleaver 400 comprises a beamsplitter 402 having a partially reflective surface 403, a first resonant cavity 404 having an inner mirror 406 and an outer mirror 408, a second resonant cavity 410 having an inner mirror 412 and an outer mirror 414, and a circulator 416 comprising a first port 416a, a second port 416b, and a third port 416c. At an input 418 coupled to first port 416a of circulator 416 is an incident beam containing a WDM signal comprising a plurality of channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$ which are usually, but not necessarily, equally spaced with a channel spacing Δf . By way of example and not by way of limitation, the channel spacing Δf may be 50 GHz, as exemplified by plot 102 of FIG. 1, *supra*. At a first output 420 coupled to partially reflective surface 403 is a WDM signal comprising the odd channels at center wavelengths $\lambda_1, \lambda_3, \lambda_5, \dots$ having a channel spacing of $2\Delta f$. Traveling back toward the input 418 is a WDM signal comprising the even channels at center wavelengths $\lambda_2, \lambda_4, \lambda_6, \dots$ also having a channel spacing of $2\Delta f$.

Circulator 416 is included to allow the incident beam to pass through to the beamsplitter 402, while separating the returning WDM signal that comprises even channels at $\lambda_2, \lambda_4, \lambda_6, \dots$ from the incident beam and directing it toward an output 422. Optical circulators are known in the art and are described, for example, in Dutton, *supra* at pp. 253-257. The components of optical interleaver 400 are preferably mounted on a low-

expansion substrate (not shown) such as Zerodur from Schott Glass Technologies, Inc. of Duryea, PA, or other suitable material.

In accordance with a preferred embodiment, resonant cavities 404 and 410 are asymmetric Fabry-Perot resonators configured as described herein. As known in the art (see, *e.g.*, Dutton, *supra* at pp. 289-296), Fabry-Perot resonators generally comprise a cavity bounded on each end by a partially-silvered mirror. Alternatively, resonant cavities 404 and 410 may be Michelson-Gires-Tournois (MGT) resonators configured as described herein. As known in the art, an MGT resonator is basically an asymmetric Fabry-Perot resonator with a partially reflecting inner mirror and a 100% reflecting outer mirror, whose operation is described, for example, in Dingel and Izutsu, "Multifunction Optical Filter With a Michelson-Gires-Tournois Interferometer for Wavelength-Division-Multiplexed Network System Applications", *Optics Letters*, Optical Society of America, Vol. 23, No. 14 (July 15, 1998), which is incorporated by reference herein.

As illustrated in FIG. 4, partially reflective surface 403 of beamsplitter 402 has a normal that is oriented at an angle θ with respect to the incident light beam. According to a preferred embodiment, the angle θ is less than 30 degrees, with robustness against input beam polarizations increasing even further as θ is reduced further. One limiting factor in reducing the angle θ is, of course, the finite physical size of the elements being placed on the low-expansion substrate, in light of a general design goal to make the overall optical interleaver of small size (*e.g.*, less than a few inches per side). However, when layout conditions permit, it has been found that an angle θ of less than 10 degrees provides excellent stability against input beam polarization.

Shown in FIG. 4 as element 409 is a round-trip path traversed by a first split beam portion of the incident beam as it travels from the partially reflective surface 403, to the resonant cavity 404, and back. Shown as element 411 is a round-trip path traversed by a second split beam portion as it travels from the partially reflective surface 403, to the resonant cavity 410, and back. Distance L_1 represents the optical path length ($\sum L_i n_i$) traversed by the first split beam portion between the partially reflective surface 403 and the resonant cavity 404. Distance d_1 represents the optical path length within resonant cavity 404. Distance L_2 represents the optical path length ($\sum L_i n_i$) traversed by the second split

beam portion between the partially reflective surface 403 and the resonant cavity 410. Finally, distance d_2 represents the optical path length within resonant cavity 410.

Optical interleaver 400 further comprises a compensating element 424 placed in one of the paths 409 or 411 between the beamsplitter 402 and resonant cavity 404 or 410, for providing thermal stability to the device. As known in the art, the glass or other optical material used in the beamsplitter 402, the resonant cavity 404, and the resonant cavity 410 will have indices of refraction n_i that will change with operating temperature, thereby changing the optical path length $\sum L_i n_i$ traversed by a beam along its respective path. In accordance with a preferred embodiment, compensating optical element 424 is placed along path 409 or 411 as required to equalize the collective thickness of optical material along these paths. Importantly, free-space distances along these paths are adjusted such that the optical path lengths L_1 and L_2 satisfy the criteria described *infra* for proper interferometric combination of the first and second split-beam portions. Thus, if the operating temperature increases and substantially changes the refractive index of the optical material, any increases or decreases in the optical paths lengths along paths 409 and 411 will offset each other, thereby providing for a thermally stable optical interleaver.

Importantly, although the index of refraction of air will also change with temperature, in general this change is small compared to the index change in optical material. Nevertheless, the inclusion of compensating optical element 424 for enhancing thermal stability is made even more effective by hermetically sealing, and optionally evacuating, the system. In accordance with a preferred embodiment, compensating element 424 is rotatably mounted with precision adjustable mountings. This allows for precise adjustment of the amount of glass introduced into the optical path during fabrication of the optical interleaver 400, so as to precisely set the center frequencies of the passbands and to precisely equalize the optical path lengths for thermal stability. These adjustments will usually be made at the factory as predetermined test signals are passed through the optical interleaver 400.

Optical interleaver 400 operates in accordance with the equations given below. For simplicity and clarity of explanation, the following equations are directed to a configuration in which Gires-Tournois resonators are used having outer mirrors that are 100% reflective, with the variable R_1 representing the reflectivity of the inner mirror of the

first Gires-Tournois resonator 404, and the variable R_2 representing the reflectivity of the inner mirror of the second Gires-Tournois resonator 410. Also used in the following equations are the following definitions: $|E_i(k)|^2$ represents the incoming beam light intensity; $|E_1(k)|^2$ represents the light intensity at output 420; $|E_2(k)|^2$ represents the light intensity at output 422; $k = (2\pi f/c)$; f = frequency of the light; and c = the speed of light in a vacuum. Finally, it is presumed that L_2 represents the optical path length of the longer interferometer arm, while L_1 represents the optical path length of the shorter interferometer arm.

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$$\frac{|E_1(k)|^2}{|E_i(k)|^2} = \frac{1}{2} + \frac{1}{2} \cos \left\{ 2k(L_2 - L_1) - 2 \tan^{-1} \left[\frac{1 - \sqrt{R_1}}{1 + \sqrt{R_1}} \tan(kd_1) \right] + 2 \tan^{-1} \left[\frac{1 - \sqrt{R_2}}{1 + \sqrt{R_2}} \tan(kd_2) \right] \right\} \quad \{1\}$$

$$\frac{|E_2(k)|^2}{|E_i(k)|^2} = \frac{1}{2} - \frac{1}{2} \cos \left\{ 2k(L_2 - L_1) - 2 \tan^{-1} \left[\frac{1 - \sqrt{R_1}}{1 + \sqrt{R_1}} \tan(kd_1) \right] + 2 \tan^{-1} \left[\frac{1 - \sqrt{R_2}}{1 + \sqrt{R_2}} \tan(kd_2) \right] \right\} \quad \{2\}$$

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As indicated by Eqs. (1) and (2), the optical path length difference ($L_2 - L_1$) determines the free spectral range of the output spectral response, and its value is set by Eq. (3) below, where Δf represents the channel spacing of the input WDM signal.

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$$L_2 - L_1 = \frac{c}{4\Delta f} = \frac{c}{2FSR_{out}} \quad \{3\}$$

Thus, generally speaking, the selection of the optical path length difference will depend on the input channel spacing Δf . For adjusting the shape of the output spectral response, the values of d_1 , d_2 , R_1 , and R_2 may be optimally selected. The most desirable characteristic, as described supra, is a box-like response with a flat top and a flat bottom.

In one preferred embodiment, desired output characteristics may be obtained by first selecting d_1 and d_2 in accordance with Eq. (4) below.

$$5 \quad d_1 = d_2 = 2 \left| L_2 - L_1 \right| = c/(2\Delta f) = c/FSR_{out} \quad \{4\}$$

Also in a preferred embodiment, in order to get a response close to the desired box-like response, the reflectivity R_2 of the inner mirror of the Gires-Tournois resonator in the longer interferometer arm should be greater than the reflectivity R_1 of the inner mirror of the Gires-Tournois resonator in the shorter interferometer arm, *i.e.*, $R_2 > R_1$. It has been found that one particularly useful set of values in the above configuration is for $R_1 = 3.3\%$ and $R_2 = 42\%$, although the scope of the preferred embodiments is not so limited. In general, it has been found that increasing the values of R_1 and R_2 will produce a more box-like passband with a flatter top and steeper sides to the response curves. However, increasing R_1 and R_2 extensively may also result in a ringing-style effect in the spectral response, resulting in increased sidelobe magnitudes that are, in turn, associated with decreased channel isolation and crosstalk.

Although the above example was given for a dual Gires-Tournois resonator implementation, it is to be appreciated that, given the present disclosure, one skilled in the art would be readily able to find suitable dimensions and surface reflectivities for more general cases using asymmetric Fabry-Perot resonators or other resonant cavities. For example, the above results are given for the computationally expedient example in which the outer mirrors of the resonant cavities are assumed to be 100%. However, it has been found that good results may be achieved even where the reflectivity of the outer mirrors falls below 100%, with good performance being realized, for example, with reflectivities greater than about 80%.

FIGS. 5A and 5B illustrate spectral characteristics of the outputs of the optical interleaver of FIG. 4, with FIG. 5A showing a plot 502 having a linear vertical axis and FIG. 5B showing a plot 504 using a logarithmic vertical axis. In particular, curve “Out1” shows the spectral response between 193.8 THz (1548.0 nm) and 194.2 THz (1544.8 nm)

for the output 420 of FIG. 4, while curve “Out2” shows the corresponding response for output 422 in this range. Figs. 5A and 5B illustrate equations (1) and (2) in graphic form and are derived therefrom. As indicated therein, a substantially improved box-like characteristic is expected to be obtained using the optical interleaver 400 based on

- 5 equations (1) and (2) with the parameters described above, for a channel spacing of $\Delta f = 50$ GHz. More particularly, it can be shown that the following spectral characteristics may be realized: $W_{0.1dB} = 0.85\Delta f$, $W_{0.5dB} = 0.88\Delta f$, $W_{3dB} = 1.00\Delta f$, $W_{20dB} = 1.18\Delta f$, and $W_{30dB} = 1.25\Delta f$. These improved spectral characteristics in turn provide for reduced crosstalk in the output signals and reduced distortion that would be caused by a non-flat passband
- 10 characteristic. It is to be appreciated that while the passbands of only four channels are shown in FIGS. 5A and 5B, the box-like response continues throughout the conventional DWDM passband of 1530-1570 nm, although the scope of the preferred embodiments is not so limited.

- Also viewable in the logarithmic plot 504 of FIG. 5B are side-lobe characteristics
- 15 506 which do allow for a nonzero amount of crosstalk between neighboring channels. Generally speaking, the peak magnitude of the side lobes may serve as an isolation metric, and is less than -45 dB for the system of FIG. 4. That is, the peak response of a neighboring channel into the channel of interest is only about 0.003% or 30 ppm (parts per million) of the magnitude of the channel of interest.

- 20 FIG. 6 illustrates an optical interleaver 600 in accordance with another preferred embodiment, comprising an input 618, a circulator 616, a beamsplitter 602 having a partially reflective surface 603, a resonant cavity 604 having an inner mirror 606 and an outer mirror 608, first and second paths 609 and 611, an optical compensating element 624 (if necessary), and outputs 620 and 622 configured in a manner similar to like-numbered
- 25 elements of optical interleaver 400 of FIG. 4. However, instead of having a resonant cavity along the path 611, optical interleaver 600 comprises a fully reflective mirror 605 positioned along path 611, thereby making the optical interleaver a single-cavity device. Although the spectral characteristics of the outputs of optical interleaver 600 are somewhat less box-like than the dual-cavity optical interleaver 400, the optical interleaver 600
- 30 nevertheless exhibits increased thermal stability due to the equalization of collective optical element thickness along the split-beam paths. Moreover, as a result of the reduced

angle θ (as compared to known prior art) between the incident beam and the normal to the partially reflective surface 603, optical interleaver 600 exhibits increased robustness against polarization of the incident beam as compared to the prior art optical interleavers described *supra*.

FIGS. 7A and 7B illustrate comparative plots of the spectral characteristics of the outputs of the optical interleavers of FIGS. 4 and 6, with FIG. 7A showing a plot 702 having a linear vertical axis and FIG. 7B showing a plot 704 using a logarithmic vertical axis. Again, Figs. 7A and 7B are derived from equations (1) and (2), using the parameters described below. $R=0$ to turn the resonant cavity into a mirror. For simplicity and clarity of disclosure, only a single output channel is shown for each system. The single-cavity plots from optical interleaver 600 use similar parameters as those given *supra* with respect to FIG. 4, except that the reflectivity R of the inner mirror 606 of the resonant cavity 604 is set to 15%. For an input channel spacing Δf of 50 GHz, the resultant spectral characteristics expected to be realized by optical interleaver 600 based on equations (1) and (2) are as follows: $W_{0.1dB} = 0.67\Delta f$, $W_{0.5dB} = 0.80\Delta f$, $W_{3dB} = 1.0\Delta f$, $W_{20dB} = 1.40\Delta f$, and $W_{30dB} = 1.52\Delta f$. In general, increasing the value of R will produce a more box-like passband with a flatter top and steeper sides to the response curves. However, similar to the dual-cavity case *supra*, increasing R extensively may also result in a ringing-style effect in the spectral response, resulting in increased sidelobe magnitudes that are, in turn, associated with decreased channel isolation and crosstalk.

It is to be appreciated that while the passbands of only four channels are shown in FIGS 7A and 7B, the box-like responses continue throughout the conventional DWDM passband of 1530-1570 nm, although the scope of the preferred embodiments is not so limited. As indicated by FIGS 7A and 7B, the dual-cavity configuration of FIG. 4 generally yields a more box-like response than the single-cavity configuration of FIG. 6. Also, the dual-cavity configuration yields better channel isolation than the single-cavity configuration (about -45 dB compared to -35 dB in this example).

FIG. 8 illustrates the optical interleaver 400 of FIG. 4 in an interleaving configuration. In accordance with reciprocity principles, the optical interleaver 400 is readily adapted to operate as an interleaver, de-interleaver, or add/drop multiplexer. Accordingly, FIG. 8 illustrates the optical interleaver 400 in an interleaving configuration,

as opposed to the de-interleaving configuration of FIG. 4. This is achieved by inputting a first WDM signal having “odd” channels at wavelengths $\lambda_1, \lambda_3, \lambda_5, \dots$ to port 420, which was formerly used as an output port in FIG. 4, these channels having a spacing of $2\Delta f$. A second WDM signal having “even” channels at wavelengths $\lambda_2, \lambda_4, \lambda_6, \dots$ is input to port 418, these channels also having a spacing of $2\Delta f$. Like before (FIG. 4), the channels at wavelengths $\lambda_2, \lambda_4, \lambda_6, \dots$ are transmitted back to the circulator 416 from beamsplitter 402. However, because the optical interleaver 400 is a reciprocal device, the channels at wavelengths $\lambda_1, \lambda_3, \lambda_5, \dots$ that are provided at input 420 are now also transmitted back into the direction of the input 418 from beamsplitter 402, and are likewise intercepted by circulator 416 and provided at the output 422. Accordingly, an interleaved output comprising a plurality of channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$ and spaced with a channel spacing Δf is provided at port 422.

FIG. 9 illustrates an add/drop multiplexer 900 in accordance with a preferred embodiment, which is substantially identical to optical interleaver 400 of FIG. 4 except that an additional circulator 902 is coupled to the output port 420. The circulator 902 comprises a first port 902a coupled to a new input 904, a second port 902b coupled to the (former) output port 420, and a third port 902c coupled to an additional output port 906. Again in keeping with reciprocity principles, and as described by the flows shown in FIG. 9, the add/drop multiplexer 900 achieves the following functionality: (i) receiving a plurality of input channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$ at a first input port 418; (ii) dropping the channels centered at $\lambda_1, \lambda_3, \lambda_5, \dots$ therefrom and providing them at the output port 906; (iii) receiving replacement channels centered at $\lambda_1, \lambda_3, \lambda_5, \dots$ (identified as $\lambda_1', \lambda_3', \lambda_5', \dots$) at the input port 904; and (iv) inserting the replacement channels into the original beam received at port 418 and providing the new beam comprising channels $\lambda_1', \lambda_2, \lambda_3', \lambda_4, \lambda_5', \lambda_6, \dots$ at output port 422.

FIG. 10 illustrates an optical interleaver 1000 that is a Mach-Zender implementation of a dual resonant element optical interleaver in accordance with a preferred embodiment. The Mach-Zender implementation may be of either the fiber or waveguide type. Optical interleaver 1000 comprises an input 1002, a first coupler 1004, a first fiber ring resonator 1006, a second fiber ring resonator 1008, a second coupler 1010, a first output 1012, and a second output 1014 coupled as shown in FIG. 10. Couplers, which

perform splitting and combining functions analogous to the beamsplitters used in the free-space implementation, are known in the art and may include resonant couplers or other coupler types. Resonant couplers are described, for example, in Dutton, *supra* at pp. 234-246. Fiber ring resonators, which perform functions analogous to the resonant cavities used in free-space implementation, are also known in the art and are described, for example, in Dutton, *supra* at pp. 297-299. An optical path distance L_1 is shown in FIG. 10 between the couplers and passing through the first fiber ring resonator 1006, while an optical path distance L_2 is shown between the couplers and passing through the second fiber ring resonator 1008.

- 10 In accordance with a preferred embodiment for an input WDM channel spacing of Δf , the parameters L_1 and L_2 should preferably be selected such that $L_2 - L_1 = c/(2\Delta f)$. The coupling ratio of each of the couplers 1004 and 1010 preferably should be 50/50. The optical path length of the fiber ring resonators preferably should each be set to $2\pi r = c/(\Delta f)$. Finally, the coupling ratios of the fiber ring resonators 1006 and 1008 preferably
- 15 should be set to $(1-R_1)$ and $(1-R_2)$, respectively, where R_1 and R_2 were the inner mirror reflectivities provided *supra* for the resonant cavities of FIG. 4. In operation, the optical interleaver 1000 may be provided with a WDM signal at input port 1002 comprising a plurality of channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$ having a channel spacing of Δf . At output 1012 will be a WDM signal comprising the odd channels at
- 20 center wavelengths $\lambda_1, \lambda_3, \lambda_5, \dots$ having a channel spacing of $2\Delta f$, and at output 1014 will be a WDM signal comprising the even channels at center wavelengths $\lambda_2, \lambda_4, \lambda_6, \dots$ also having a channel spacing of $2\Delta f$. A single-ring resonator in accordance with the preferred embodiments may also be made by eliminating the fiber ring resonator in the longer optical path (*i.e.*, the fiber ring resonator 1008) and appropriately adjusting the coupling
- 25 ratio of fiber ring resonator 1006.

- FIG. 11 illustrates the optical interleaver 1000 of FIG. 10 in an add/drop multiplexer configuration. As illustrated in FIG. 11, when provided with an additional input 1003 into the coupler 1004, the optical interleaver 1000 may perform as an add/drop multiplexer and achieve the following functionality: (i) receiving a plurality of input
- 30 channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \dots$ at input port 1002; (ii) dropping the channels centered at $\lambda_1, \lambda_3, \lambda_5, \dots$ therefrom and providing them at the output port 1012;

(iii) receiving replacement channels centered at $\lambda_1, \lambda_3, \lambda_5, \dots$ (identified as $\lambda_1', \lambda_3', \lambda_5', \dots$) at the input port 1003; and (iv) inserting the replacement channels into the original beam received at port 1002 and providing the new beam comprising channels $\lambda_1', \lambda_2, \lambda_3', \lambda_4, \lambda_5', \lambda_6, \dots$ at output port 1014.

- 5 Multiple optical interleavers according to the preferred embodiments may be placed in a parallel-cascade fashion to achieve even further channel configuration. For example, an input WDM signal comprising multiple channels at center wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}, \dots$ spaced by Δf may be provided to a first-stage optical interleaver to generate a first output having center wavelengths at $\lambda_1, \lambda_3, \lambda_5, \lambda_7, \lambda_9, \dots$ spaced by $2\Delta f$ and
- 10 a second output having center wavelengths at $\lambda_2, \lambda_4, \lambda_6, \lambda_8, \lambda_{10}, \dots$, also spaced by $2\Delta f$. The first output of the first-stage optical interleaver may then be provided to a first second-stage optical interleaver to generate a third output having center wavelengths at $\lambda_1, \lambda_5, \lambda_9, \dots$ spaced by $4\Delta f$ and a fourth output having center wavelengths at $\lambda_3, \lambda_7, \lambda_{11}, \dots$ also spaced by $4\Delta f$. respectively. Likewise, the second output of the first-stage optical
- 15 interleaver may be provided to a second second-stage optical interleaver to generate a fifth output having center wavelengths at $\lambda_2, \lambda_6, \lambda_{10}, \dots$ spaced by $4\Delta f$ and a sixth output having center wavelengths at $\lambda_4, \lambda_8, \lambda_{12}, \dots$ also spaced by $4\Delta f$. Thus, if international standards develop further to make DWDM channel spacings even more dense, conventional dichroic filters may still be employed where the DWDM signals are first provided to multiple
- 20 optical interleavers in a parallel-cascade fashion that increase the channel spacings to a distance where dichroic filters are effective.

- 25 In the embodiments illustrated in Figs. 4 and 6, an initial optical signal impinges at an angle substantially less than 45° on a device such as a beam splitter and divides thereby into a first and a second input optical signals. In Fig. 10, a coupler 1004 divides the initial beam. The resulting first and second input optical signals are processed in Fig. 4 by resonators 404 & 410, in Fig. 6 by resonator 604 and mirror 605, and in Fig. 10 by resonators 1006 & 1008 to thereby produce respective first and second processed optical signals. Where a resonator processes an input optical signal that has frequency band with sloping shoulders in a spectral power versus frequency plot, as is the case with the bands
- 30 illustrated in Figs. 1 & 2, the processing alters the phase of the signals such that, when interferometrically recombined, these shoulders are substantially preserved, because the

passbands are more box-like such as those illustrated in Figs. 5A, 5B, 7A and 7B. The processed optical signals are combined, such as at elements 402, 602 and 1010, to thereby produce respective first and second output optical signals. One of the output optical signals has spectral power bands that match one subset of the bands in the initial optical signal, e.g., the even-numbered bands, and the other matches another subset, e.g., the odd-numbered bands. Thus, as illustrated in Fig. 5A and 5B for example, one of the output optical signals will have spectral power bands within those of the plot labeled "Out 1" in the figure, which transmittance bands that are generally centered at 193.8 THz, 193.9 THz, 194 THz, etc. Information outside the transmission bands of the signal labeled "Out 1" is suppressed. The transmission bands of the "Out 1" plot and those of the other output ("Out 2") alternate as illustrated, and each matches a respective different subset of the bands in the initial signal.

Whereas many alterations and modifications of the present invention will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that the particular embodiments shown and described by way of illustration are in no way intended to be considered limiting. As a non-limiting example, in view of the principles described above, it would be within the scope of the preferred embodiments to provide an optical interleaver in which more than one resonant cavity is placed in each split beam path. Therefore, reference to the details of the preferred embodiments are not intended to limit their scope, which is limited only by the scope of the claims set forth below, as they may be amended before the grant of a patent.